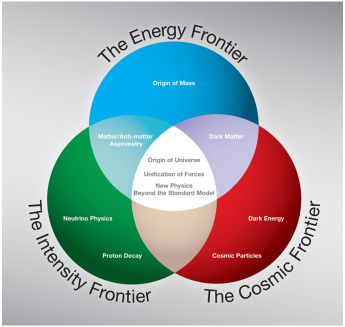
Lecture 2: Detectors and Accelerators (Part I)

Fall 2016
August 30, 2016

Reminder: The 3 frontiers

- Energy Frontier
  - Use high energy colliders to discover new particles and new interactions and directly probe the fundamental forces
- Intensity Frontier
  - Use intense particle beams or large mass detectors to uncover the properties of neutrinos and to observe rare processes that involve other elementary particles
- Cosmic Frontier
  - Use underground experiments and telescopes to study Dark Matter and Dark Energy. Use high energy particles from space to search for new phenomena



Particle Physics Strategies

- Create new particles through high energy collisions
  - $E = mc^2$
  - Examples: e^+e^- or hadron colliders
- Scatter particles (beam) from a target to either:
  - Study structure of the target
    - eg Rutherford scattering or structure of proton
  - Understand interaction between beam and target
    - eg Study weak neutral current using ν-p scattering
- Study particle decays
  - Use decay rates and kinematics to either:
    - Understand internal structure (spectroscopy)
    - Study symmetry properties of interactions
    - Confirm detailed SM predictions

Accelerator vs Non-accelerator Experiments

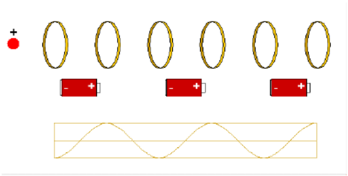
- Previous slide focused on discussion of beams
  - Often implies man-made beams from accelerators
- But can also use "beams" from nature
  - eg ν or Dark Matter particles from outer space

  or from other man-made sources
  - eg ν from reactors
- Possibilities also exist for experimenets without a beam
  - eg proton decay
  - Astrophysical measurements

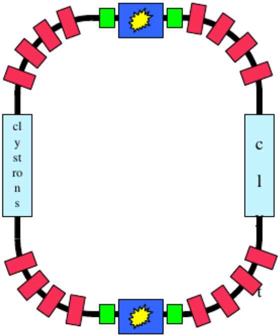
Today and Thursday, we'll explore how experimental goals and strategies affect detector and accelerator design

Accelerators: Using particle beams to probe the energy and intensity frontiers

- Charged particles “surf” on EM waves produced from RF cavities



- Magnetic fields used to steer the beams



Will discuss how accelerators work in Thursday’s leccture

Fixed Target vs Collider

- Colliding Beams:

$$E_{cm} = \sqrt{4E_1E_2}$$

  - In center-of-mass
  - All energy available for hard scattering and/or creation of new particles

- Fixed Target:

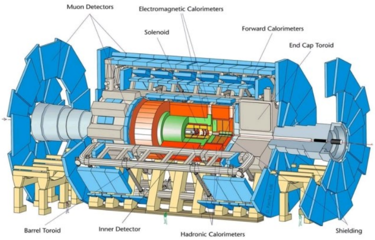
$$E_{cm} = \sqrt{2m_{target}E_{beam}}$$

  - Kinetic energy of final state means less available for producing new particles
  - Variety of targets and beams
    - including beams of unstable particles
    - Larger target mass, higher event rates

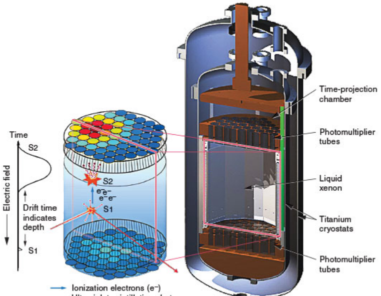
Configuration of multiple detector elements

- Most experiments combine different detector technologies
  - Each emphasizes different type of measurement
- Geometry determined by type of "beam":
  - Collider, fixed target, non-accelerator
- Granularity determined by # particles per event
- Required resolution depends on
  - Momentum and energy of produced particles
  - Backgrounds to be rejected
  - Necessary precision

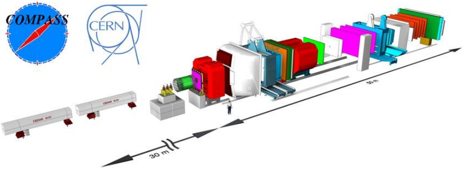
ATLAS (Collider)



LUX (Underground DM Detector)



Compass ν experiment (Fixed target)



Classification of particle detectors: What do we measure?

- Charged Particles
  - Momentum: Determine trajectory in B field
  - Mass: More difficult; Measurement of velocity and momentum
  - Energy: Deposited as particle stops.
    - Energy loss from ionization, bremsstrahlung

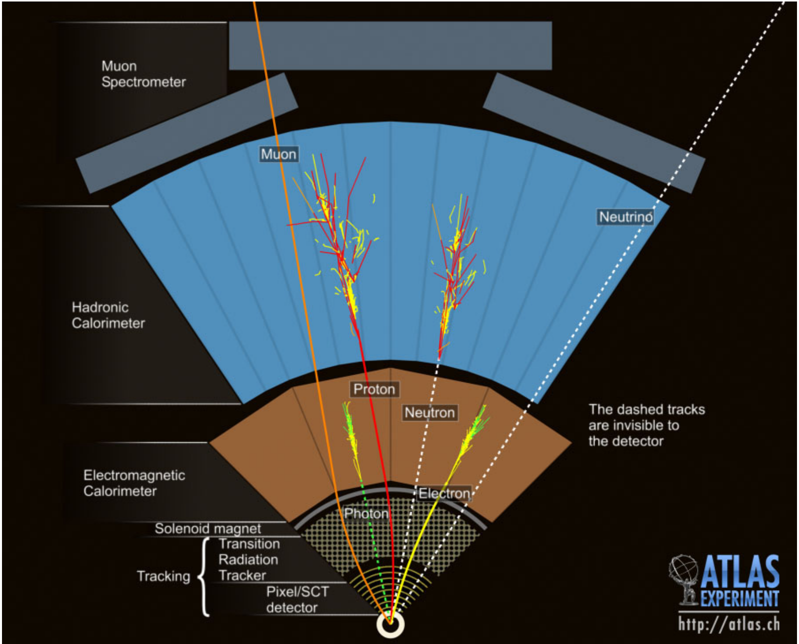
Tracking Detectors

- Strongly Interacting Particles (charged or neutral)
  - Energy: Deposited where particle stops
    - Energy loss from nuclear interactions
- Photons
  - Energy: Pair production followed by ionization

Calorimeters

- Muons
  - Momentum: As for other charged particles
  - No nuclear interactions
    - Can pass through lots of matter before stopping
    - Additional tracking detectors after calorimeter
- Neutrinos
  - Often observed by their absence: missing momentum
  - Weak interactions with nucleus, eg $\nu_\mu N^Z \to \mu^- N^{Z+1}$

How it works:

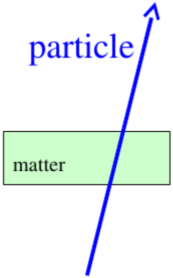

Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

Interaction of particles with matter

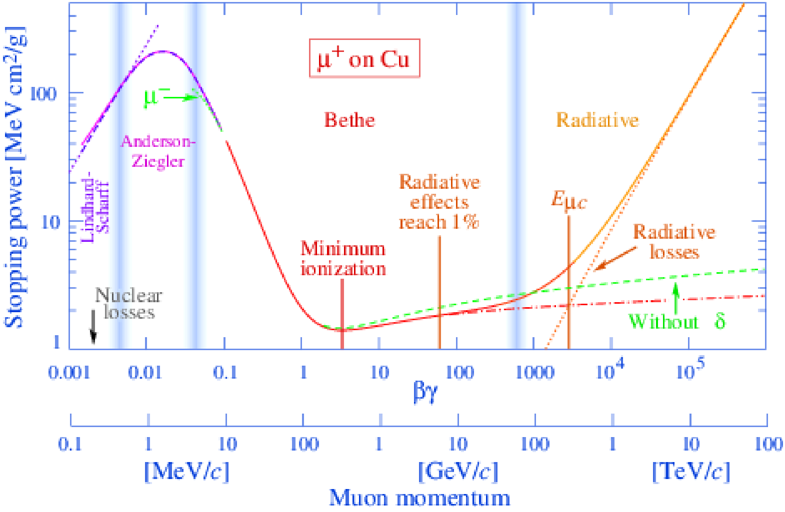
- Except for hadron calorimeters and ν-detectors, particle detection depends on EM interaction of particle with detector element
  - Even for these exceptions EM interactions dominate detection of secondaries
- Charged particles leave ionization trail
  - Amount of ionization per unit length depends on velocity
  - Total ionization produced when particle stops measured from number of ionizing particles produced in "shower"
- Statistical description of ionization energy loss

Charge particle interactions with matter

- Charged particles deposit energy in matter
  - Ionization
    - Average ionization energy loss (dE/dx)
    - Fluctuations in ionization deposition
  - Light
    - Scintillation
    - Cerenkov radiation
    - Transition radiation
- Matter affects charged particles
  - Multiple scattering
  - Bremsstrahlung



Energy loss in Matter (particles heavier than electrons)



Energy loss at intermediate energies

- Bethe-Block Formula

$$-\frac{dE}{dx} = 4\pi \frac{z^2\alpha^2}{\beta^2} \frac{Z\rho}{Am_N m_e} \left[\frac{1}{2} \ln \frac{2m_e \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

m_e, m_N, α—universal constants:
electron and nucleon masses; fine structure constant;

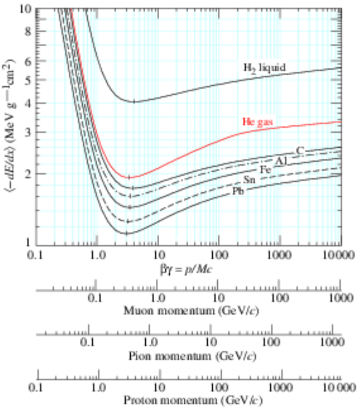
z, β, γ—**incoming particle parameters:**
charge in units of e, velocity β=v/c, gamma factor)

Z, A, ρ, I—**media properties**:
charge and atomic number, density, average ionization potential

T_{max} – maximum energy that can be transferred
from an incoming particle of mass m to an electron

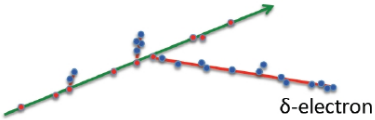
$$T_{\max} = \frac{2m_e \beta^2 \gamma^2}{1 + 2\gamma (m_e / m) + (m_e / m)^2}$$

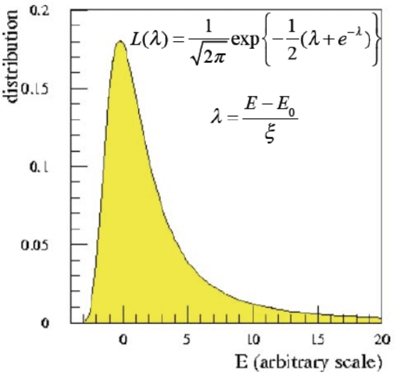
δ—small correction due to media polarization
(for gasses, it is negligibly small)



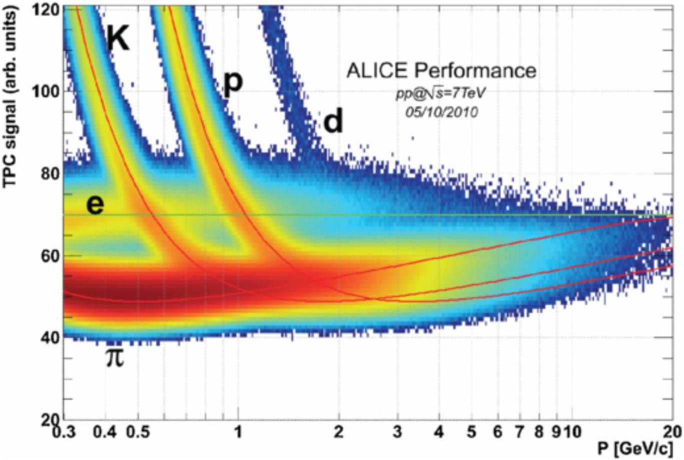
dE/dx fluctuations

- Charged particles ionize the material they traverse
  - Ionization forms mini-tracks
  - Most ionization at low energy
    - Electrons stop close to ionization point
  - Hard long tail called "delta-rays"
    - These can travel some distance
  - Best measure of dE/dx is truncated mean:
    - Measure energy loss multiple times in thin samples
    - Remove a fixed fraction of the measurements at the high end
    - Take the mean of the rest
    - Unbiased estimator of β





dE/dx for particle identification



- dE/dx depends on $\beta\gamma$ and p : $\Rightarrow$ depends on mass
- Can distinguish between e, π, K, p at low momentum

Multiple Coulomb Scattering

- Rutherford scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{zZ\alpha}{\beta p}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

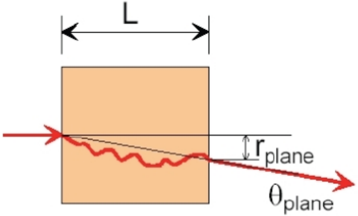
- Random walk: N steps of size d: Total deviation is Gaussianly distributed with width D:

$$D \sim \sqrt{dN}$$

- Resulting angular spread

$$\theta_{rms} = (14\ MeV)\frac{z}{\beta l}\sqrt{L/X_0}$$

$$r_{rms} = \frac{1}{\sqrt{3}} L\theta_{rms}$$



- where X_0 is the "radiation length" of the material:

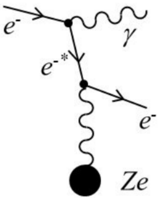
$$\frac{1}{X_0} = Z(Z+1)\frac{\rho}{A}\frac{\ln\left(287/Z^{\frac{1}{2}}\right)}{716\ \mathrm{g/cm^2}}$$

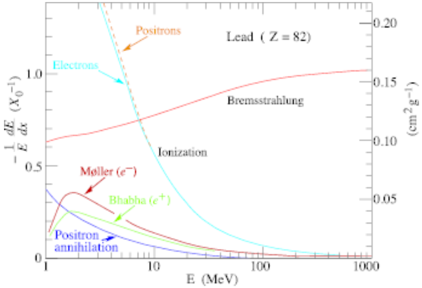
Bremsstrahlung

- Radiation of photons from charged particles
  - Can carry away a large fraction of energy
  - Energy loss increases with incident energy

For electrons $\frac{dE}{dx} = -\frac{E}{X_0}$

- Critical energy
  - Energy where losses from brem equal those from ionization
    - Electrons: 20 MeV in iron
    - Muons: ~ 1 TeV in iron





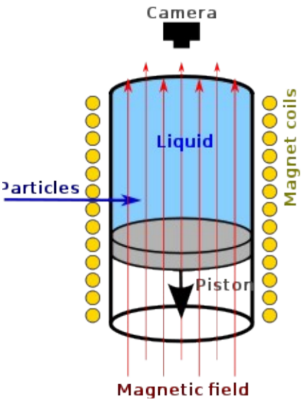
Tracking Detectors

- Tracking Detectors observe and measure the properties of charged particles
- Goal is to determine:
  - Trajectory
  - Momentum
  - (species or mass)
- Often placed in magnetic field; curvature to find momentum
- Often measure ionization trail (although other possibilities as well)
- Combination of tracks originating from one spot can be used to isolate a vertex from interaction or decay of particles

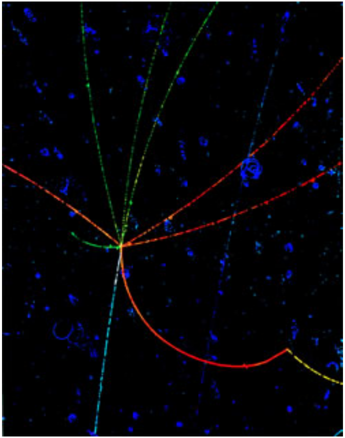
Bubble Chambers

- Large cylindrical tank of liquid heated to just below boiling point
- Piston suddenly desceases pressure $\Rightarrow$ liquid in superheated phase
- Charged particles leave ionization track; liquid vaporises around track
  - Bubbles!
  - Bubble density proportional to dE/dx
- Drawbacks:
  - Photographic readout
  - Difficult to "trigger" on events
  - Cannot reset quickly

Don Glaser Nobel Prize 1960



Bubble Chamber Picture of Proton-antiProton Annihilation



http://www2.lbl.gov/Science-Articles/Archive/sabl/2005/October/01-antiproton.html

An antiproton (blue) enters a bubble chamber from bottom left and strikes a proton.

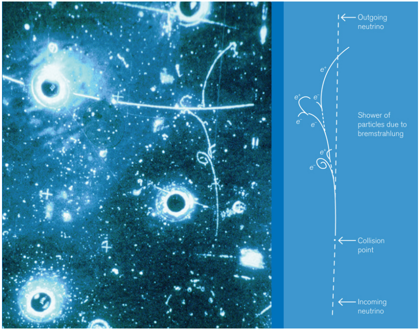
The released energy creates four positive pions (red) and four negative pions (green).

The yellow streak at the far right is a muon, a decay product of the adjacent pion.

Gargamelle and the Discovery of Neutral Currents

Gargamelle at CERN

Diameter: 2m, Length 4.8m



- Discovery of neutral weak currents in 1973
- Critical for establishing electroweak theory

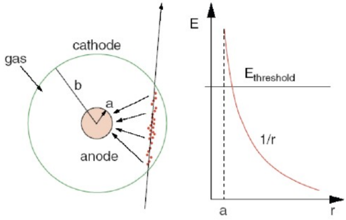
$$\nu_\mu + e^- \to \nu_\mu + e^-$$

Gaseous Wire Chambers

- PC, MWPC, DT, CSC, ...
- Ionization signal in gas leaves ~ 100 electrons/cm
  - Too few to detect
- Solution:

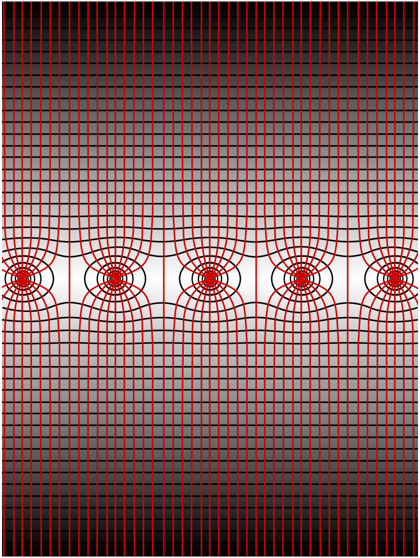
  Introduce thin wires (20-100μm) at positive HV (few kV) for gas multiplication

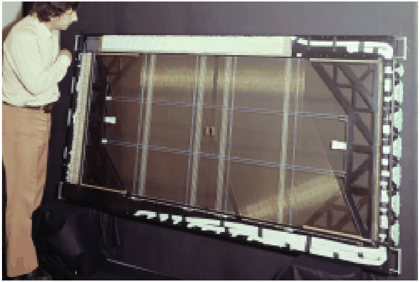
  - Field $E \sim 1/r$
  - Avalanche developes with overall multiplication (gas gain) controllable by adjusting voltage



Example: Geiger counter

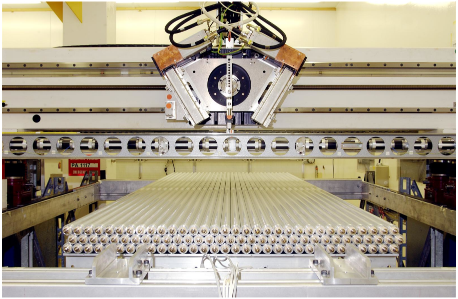
Multiwire Proportional Chambers

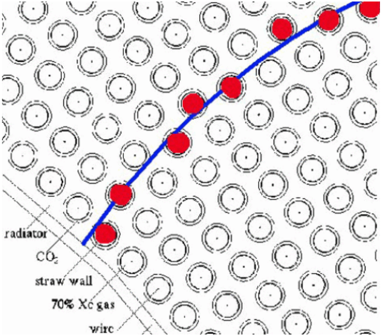




- For many years, a mainstay in HEP experiments
- Position resolution determined by wire spacing (few mm)
- Some chambers have etched pads on the cathode to provide measurement along wire direction

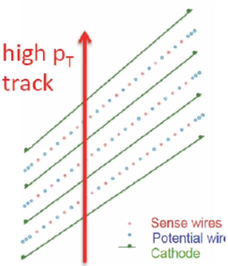
Drift Tubes

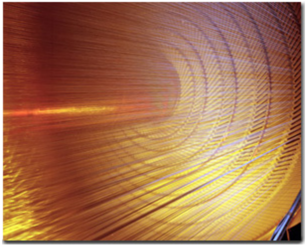




- Know when particle goes through detector (t_0)
- Measurement drift time $\Delta t = t - t_0$
  - Drift distance: $x = f(\Delta t)$
- Typical resolution: 100-200 μm

Multiwire Drift Chambers



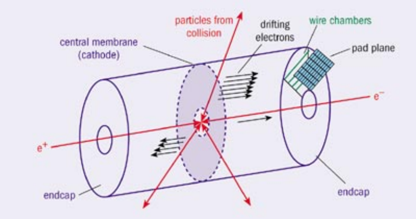


CDF Drift Chamber

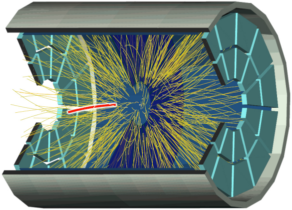
96 radial layers of gold wires spaced 3.9 mm from each other

- Similar to drift tubes but without individual tubes
- Both flat-plane and cylindrical geometries possible
- Can cover large surface areas

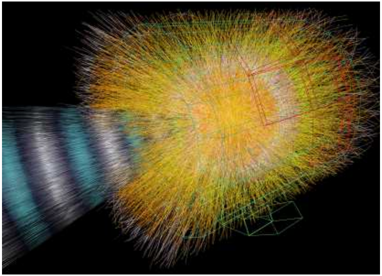
Time Production Chamber (TPC)



STAR TPC



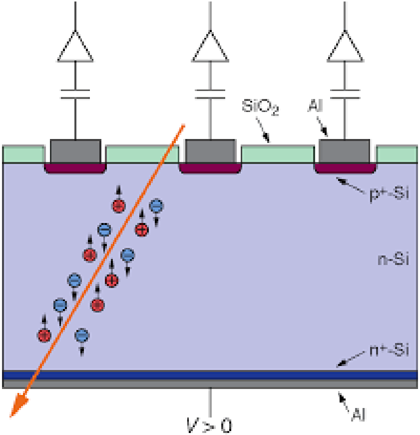
ALICE TPC



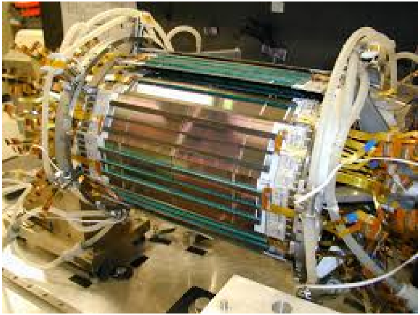
- Long drift distance
- Ionization collected at ends
- Very little material in tracking volume
- Good two-track resolution

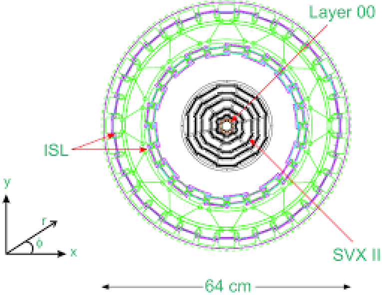
Solid State Detectors: Semiconductor Devices

- Inverse potential applied to p-n junction (reverse bias) in Si creates large volume depleted of charge carrier
  - Semiconductor behaves as insulator with no current flowing
- Ionization (from charged particles traversing sensor) release electron-hole pairs that drift apart and are collected on either side of sensor

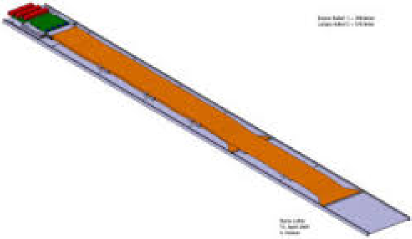


Silicon Strip Detectors

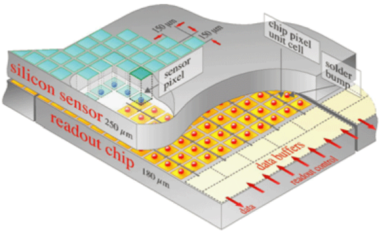


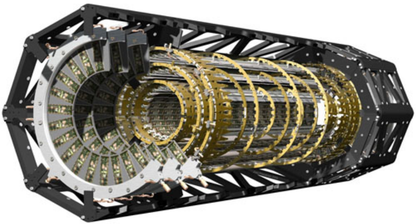


- Strips etched onto silicon waifer
  - Typical size of waifter: 3cm x 6 cm
  - Typical strip pitch: 50-100 μm
- One amplifier per strip
  - Only hit strips sent to data acquisition system



Pixel Detectors: Same idea, more channels

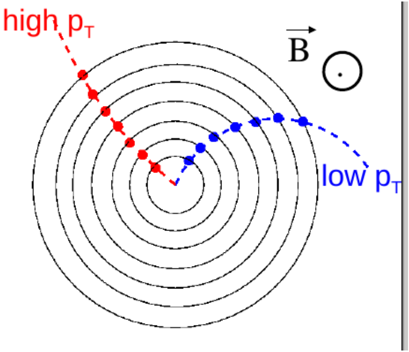




- Instead of long strips, 2D rectangles
- Electronics mounted on top of each pixel
- Example: ATLAS pixel detector
  - 1744 modules
  - 80 million pixels
  - Pixel size: 50μm x 400μm
  - Resolutiion 10μm in bending plane

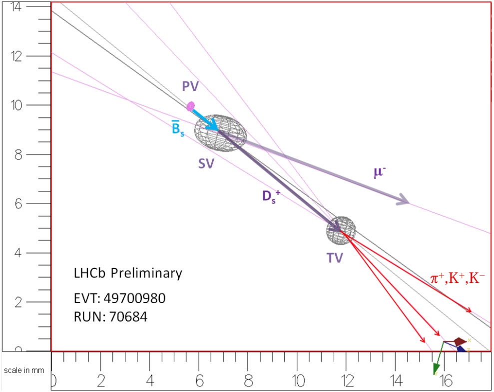
Track Reconstruction

- Charged particles traverse many laters of detectors
- Detectors often placed in magnetic field
  - Lorenz force $F = qv \times B$
- Hits along trajectort are "fit" to form a track
  - Deviation from straight line proportonal to momentum
  - Direction of curvature gives sign of charge



$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{720}{N+4}} \frac{\sigma_x}{qBL^2} p_T$$

Vertex Reconstruction



- Extrapolate tracks to common vertex point
- Resolutuion on measurement of vertex location depends on extrapolation of track trajectory
  - Good position resolution required
  - First measurement should be close to beam line
  - Minimize amount of material